PAPER

Satellite Environmental Monitoring of the Great Lakes: Great Lakes CoastWatch Program Update

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ABSTRACT

As the CoastWatch regional node for the Great Lakes, the Great Lakes Environmental Research Laboratory (GLERL) obtains, processes, and delivers environmental data and products for the user community. GLERL provides access to near real-time satellite observations and in situ *data for the Great Lakes to 41 federal, state, and local agencies and academic institutions. The goals and objectives of the CoastWatch Program directly support NOAA statutory responsibilities in estuarine and marine science, living marine resource protection, and ecosystem monitoring and management. A digital image product suite of 26 images from the NOAA-12, NOAA-14, and GOES 8 satellites is currently being received. Over 32,000 image products have been received and archived since 1990. In addition,* in situ *and modeled data, including marine and meteorological observations and water level gauge measurements, are also routinely received and made available via dial-in modem or Internet. A new product developed at GLERL, the Great Lakes Surface Environmental Analysis (GLSEA), is a cloud-free, composited surface temperature chart that will include an ice cover analysis overlay during winter months. It is available to CoastWatch data users and is also on the World Wide Web.*

INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) CoastWatch Program evolved from a program developed by NOAA's National Environmental, Satellite, and Data Information Service (NESDIS) to provide the NOAA National Marine Fisheries Service Laboratory at Beaufort, North Carolina with satellite-derived sea surface temperature (SST) maps of the Gulf Stream so that future occurrences of the "red tide" that occurred off the North Carolina coast in late 1987, or other coastal environmental events could be better anticipated and monitored (Pyke, 1989). This program has since been extended to other coastal regions in the United States including the Great Lakes. Figure 1 shows current CoastWatch regional sites. The goal of the CoastWatch program is to develop and deliver environmental data and products for near real-time monitoring of U.S. coastal waters to support environmental science and decision-making. The objectives of CoastWatch are: 1) to provide access to near real-time and retrospective satellite and aircraft observations of the U.S. coastal ocean for federal, state, and local decision-making, 2) to integrate workstations and associated software systems for analyses of environmental quality, coastal hazards, and wetlands change, 3) to develop a communications system supporting distribution of near real-time and historical satellite and *in situ* observations to national and regional coastal users, and 4) to develop and implement a database management and display system supporting integrated coastal ocean applications. NOAA CoastWatch directly supports agency statutory responsibilities in estuarine and marine science, living marine resource protection, and ecosystem monitoring and management contained in several federal environmental statutes, including the U.S.-Canadian Great Lakes Water Quality Agreement.

In 1990, as part of the CoastWatch program, NOAA's Great Lakes Environmental Research Laboratory (GLERL) located in Ann Arbor, Michigan was chosen as the CoastWatch Regional Site for the Great Lakes. The initial CoastWatch product for the Great Lakes was digital imagery of lake surface temperature at pixel sizes of 1.3 and 2.6 km, derived from NOAA satellite data. Mapped to a Mercator projection, several of these images per day were received electronically at GLERL beginning in April 1990. In addition, *in situ* and modeled data products were received including Marine Observation Data and Fields by Information Blending (FIB) gridded atmospheric pressure and wind field data. GLERL is currently receiving a daily image product suite of 26 types of satellite images, including surface temperature, visible and near-infrared reflectance, brightness temperatures, satellite and solar zenith angle data, and cloud masks (see Table 1 for description). Marine observation data and water level gauge data are also being received and made available. Figure 2 summarizes the acquisition of the Great Lakes CoastWatch product suite since April 1990.

As a CoastWatch Regional Site (CRS), GLERL is making Great Lakes CoastWatch products available to other regional users. The first Great Lakes regional user site was established at the Center for Great Lakes Studies at the University of Wisconsin-Milwaukee in 1990. Since then, regional users have grown in number to include 41 active users from federal, state, and local government agencies, organizations engaged in cooperative research programs with NOAA, and academic institutions in the United States and Canada.

Figure 1. CoastWatch Regional Nodes and Sites.

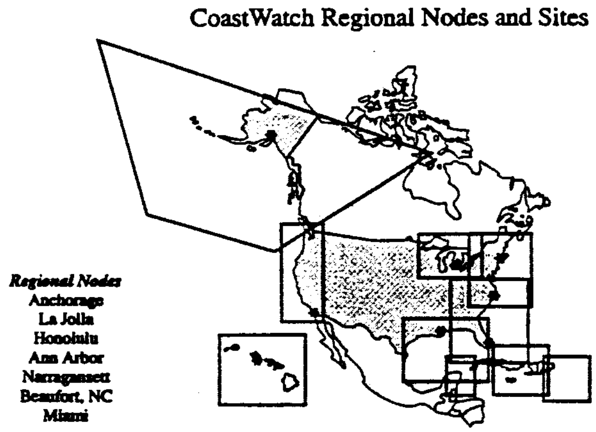


Table 1. Currently Available Great Lakes CoastWatch Products

Product Code	Disc Directory	Product Type
C1	[CW.xC1.yr]	Channel 1 albedo
C2	[CW.xC2.yr]	Channel 2 albedo
C3	[CW.LC3.yr]	Channel 3 brightness temperatures (synoptic)
C4	[CW.LC4.yr]	Channel 4 brightness temperatures (synoptic)
C5	[CW.LC5.yr]	Channel 5 brightness temperatures (synoptic)
CM	[CW.xCM.yr]	Cloud mask
D1	[CW.xD1.yr]	Daytime split window SST (NOAA 11) (OCNMAP/MCSST)
S7	[CW.xS7.yr]	Nighttime split-window SST (NOAA 11) (OCNMAP/NLSST)
CT	[CW.LCT.yr]	Great Lakes Surface Environmental Analysis (GLSEA)
ZA	[CW.xZA.yr]	Solar zenith angle
ZS	[CW.xZS.yr]	Satellite zenith angle (synoptic)
MO	[CW.LMO.yr]	Great Lakes Marine Observation Network synoptic meteorological observations
WL	[CW.LWL.yr]	Synoptic water level data (hourly)
WM	[CW.LWM.yr]	Synoptic mean water level data (daily)
GI	[CW.LGI.yr]	GOES infrared channel Great Lakes subscene (hourly)
GV	[CW.LGV.yr]	GOES visible channel Great Lakes subscene (hourly daytime)

x = A single character scene identifier:

L = Great Lakes synoptic scene

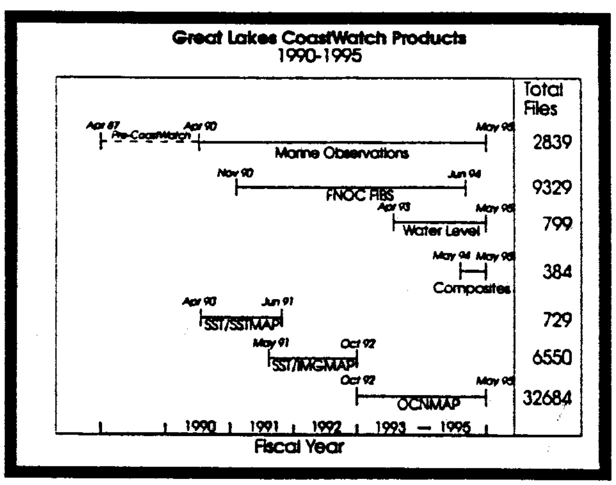
S = Lake Superior high resolution subscene

M = Lakes Michigan and Huron high resolution subscene

E = Lakes Erie and Ontario high resolution subscene

yr = Last two digits of year

Figure 2. Great Lakes CoastWatch Products—1990–1995.

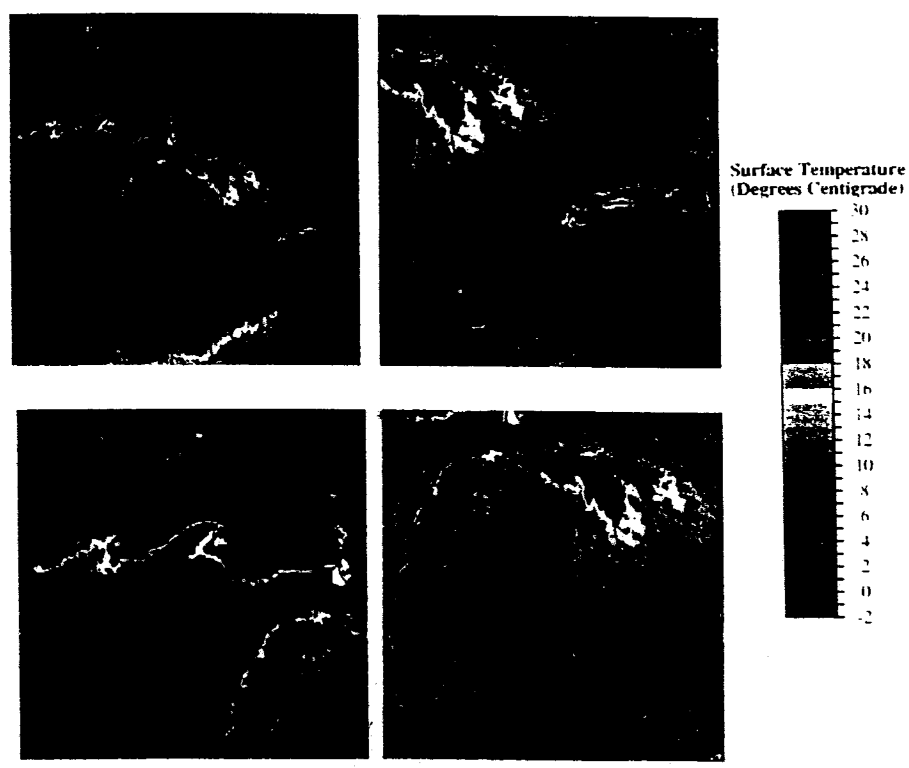


DATA / PRODUCTS

Current CoastWatch image products are obtained from NOAA polar-orbiting weather satellites. There are currently two operational polar-orbiting weather satellites (NOAA-12 and NOAA-14), which each carry (among other sensors) the Advanced Very High Resolution Radiometer (AVHRR). Initial CoastWatch surface temperature imagery received was produced from NOAA-10 and NOAA-11 data. As NOAA-14, launched on 30 December 1994, has recently become operational, current image products are produced from NOAA-12 and NOAA-14 data. NOAA polar-orbiting satellites are in a sun-synchronous orbit at an altitude of approximately 833 km. Each satellite passes over a given area twice a day: about 2 a.m. and 2 p.m. local time for NOAA-14 and about 7 a.m. and 7 p.m. local time for NOAA-12. The AVHRR scans a swath of approximately 2700 km on the earth's surface beneath the satellite in five wavelength bands, Ch.1—visible (0.58–0.68 μm), Ch.2—reflected infrared (0.725–1.0 μm), and three thermal infrared bands (Ch.3—3.55–3.93 μm, Ch.4—10.3–11.3 μm, Ch.5—11.5–12.5 μm) (Koczor, 1987). AVHRR data are processed at two resolutions, 4 km Global Area Coverage (GAC) and 1 km Local Area Coverage (LAC) and High Resolution Picture Transmission (HRPT). The HRPT data are used for Great Lakes CoastWatch imagery. These data are downloaded to a satellite receiving station, then transmitted to NESDIS facilities in Suitland, Maryland where they are calibrated, geo-located, quality controlled, and made available as AVHRR Level 1B data sets (see Kidwell, 1991 and Pichel et al., 1991 for details of this process). For the CoastWatch program, the Level-1B data are mapped to a Mercator projection and resampled to a 512×512 pixel grid. Four scenes or "windows" are extracted for the Great Lakes region as shown in Figure 3. One synoptic scene covers all five lakes at a 2.56 km resolution (scene center). The other three scenes focus on Lake Superior, Lakes Michigan and Huron, and Lakes Erie and Ontario at twice the resolution of the five-lake scene. Actual resolution is determined by d cos ϕ, where d is the spatial resolution at the equator, and ϕ is the latitude. Pixel sizes at mid-latitude for the three high resolution Great Lakes scenes range from 1.24 to 1.30 km.

Applications of temperature and reflectance imagery to the analysis of lake physics are numerous. Bolgrien and Brooks (1992) describe and illustrate the development of vernal thermal fronts and other thermal features in

Figure 3. Surface temperature images for each of the four Great Lakes CoastWatch "scenes." (a) Lake Erie/Ontario scene, (b) Lake Michigan/Huron scene, (c)Synoptic Scene, (d) Lake Superior scene.



Lake Michigan using CoastWatch temperature imagery. Schwab et al. (1992) demonstrate the potential utility of CoastWatch temperature imagery for monitoring thermal fronts, analyzing surface circulation patterns, and aiding in the detection and mapping of ice cover. The satellite-derived temperature imagery and other *in situ* data are also being routinely used for the Great Lakes Forecasting System model input and verification as described by Schwab and Bedford (1994).

SURFACE TEMPERATURE

Surface temperature is calculated for each pixel in the scene using the equations described below. The mapped surface temperature images are stored in computer files as 11-bit integers and can be converted to temperature as follows:

$$0 < n \leq 920 \ : SST = 0.10n + 178$$
$$920 < n \leq 1720 : SST = 270 + 0.05\,(n\text{-}920)$$
$$1720 < n \leq 4095 : SST = 310 + 0.10\,(n\text{-}1720)$$

where n is the 11-bit integer and SST is in degrees Kelvin. This mapping provides a 0.05°C resolution over the main region of interest for water temperatures. Four bits of graphics information including lake shorelines, state boundaries, and a latitude-longitude reference grid are appended to the temperature data. A data compression technique is used to minimize data storage requirements and speed data transmission (see Leshkevich et al., 1993 and Maturi and Taggart, 1993 for detail).

VISIBLE/NEAR-INFRARED BANDS—SATELLITE/SOLAR ZENITH ANGLE

Visible (Channel 1) and near infrared (Channel 2) reflectance imagery is being received for all four scene windows. In addition, satellite zenith angle data are received for the synoptic scene window and solar zenith angle data for all scene windows.

MARINE OBSERVATIONS—WATER LEVEL GAUGE DATA

Marine weather observations from stations in the Great Lakes region are routinely collected by the NOAA National Weather Service Forecast Office at Cleveland, Ohio. GLERL has downloaded and archived this data since August 1987. The observation network is comprised of 117 fixed stations, including 14 moored buoys, 8 CMAN (Coastal Marine Automated Network) stations, 30 United States Coast Guard stations, 10 OMR (Other Marine Reports (wind data only)) stations, 11 surface synoptic stations, and 44 surface airways stations. In addition, many commercial cargo ships provide regular meteorological reports, which are also included in this data base. Frequency of observational reporting ranges from twice per hour to once every three hours depending on the type of station. The GLERL database includes the following information extracted from Great Lakes marine weather observations: air temperature, dew point, wind direction, wind speed, maximum wind gust, cloud cover, air pressure, water temperature, wave height, and wave period. Most stations usually do not provide all the fields in the above list, but buoys and CMAN stations provide the most complete and reliable data sets.

Water level gauge data from 22 telemetered stations around the Great Lakes are downloaded from the National Ocean Service (NOS) and made available to Great Lakes CoastWatch users on a trial basis.

NEW PRODUCTS

Several new products have been developed using CoastWatch imagery that enhance its utility or result from models using the image data as input. These are summarized below.

Cloud Masks

Analysis of CoastWatch satellite surface temperature and visible imagery is hindered by the presence of cloud cover. A cloud mask product has been developed and is available for masking out all clouds present in CoastWatch satellite imagery products (Maturi and Pichel, 1993). A cloud mask product is necessary to determine cloud-free areas for correct surface temperature identification and for creation of subsequent products.

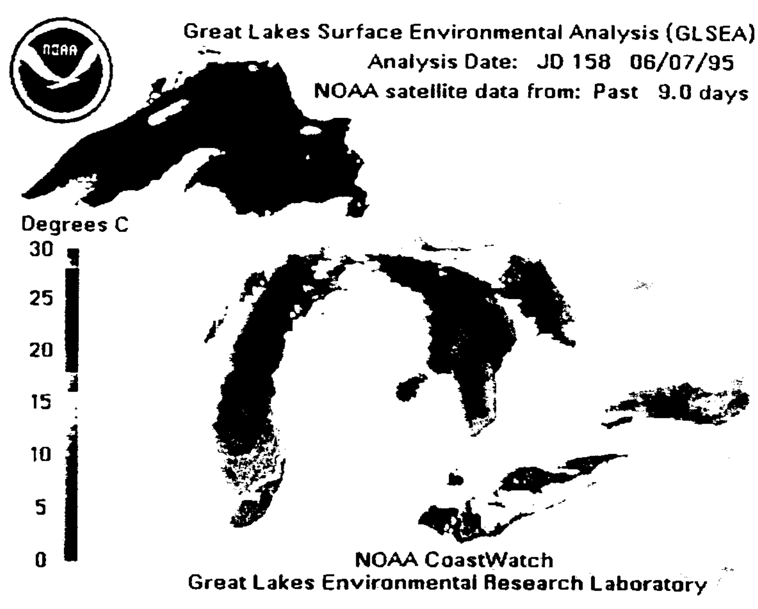
Great Lakes Surface Environmental Analysis (GLSEA)

Individual SST images are typically obscured by clouds to a greater or lesser extent depending mainly on the time of year. At GLERL, a method was developed for composing individual SST images in space and time to provide complete daily SST fields for all five lakes.

Currently, synoptic scenes (512 × 512, 2.6 km pixels) from NOAA-14 are the basis for the composite map. When a synoptic scene is received, it is processed to estimate an optimal linear geocorrection to position the scene within the window. The geocorrection is expressed as an east-west displacement value and a north-south displacement value. When these values are determined, the images are shifted accordingly. The images are then land-masked so that only over-water pixels are considered. To estimate which pixels are cloud-covered, the cloud masks (determined using different cloud test algorithms) are applied to their respective daytime or nighttime image. Next, if the SST is less than 0 for a pixel, it is masked. All remaining pixels are then used to compute an average and a standard deviation for the 9 pixel box around each pixel. If a pixel has no neighbors, it is masked. If the standard deviation of SST is greater than 3 degrees, the pixel is masked. Unmasked pixels are replaced by the 9 pixel average.

To form a composite temperature map, the pixels that pass the above screening tests are overlayed on the previous day's composite map, but only if their total area for each lake (Superior, Michigan, Huron, St. Clair, Erie, Ontario) is at least 5 percent of the lake surface area. If the valid area for a lake is greater than 20 percent of the lake area, then the average temperature for the valid area is computed both from the new pixels and from the previous day's composite. All pixels for this lake in the previous day's composite are adjusted by the difference between these average values. The new composite scene is smoothed with a 9-point average. Finally, the current daily composite scene is averaged with the scenes from the previous 4 days to create a 5-day composite (Figure 4). It should be noted the data used to produce the composite scene can be older than five days depending on location and duration of cloud cover.

Figure 4. Great Lakes Surface Environmental Analysis (GLSEA).



Great Lakes Forecasting System Products

The Great Lakes Forecasting System is a real-time coastal prediction system for forecasting, on a daily basis, the physical state of each of the Great Lakes for the next two days (Schwab and Bedford, 1994). Forecast variables include surface water level fluctuation, waves, horizontal and vertical structure of temperature and currents, and turbulence. The system uses meteorological observations, satellite data, and forecasts from numerical weather prediction models as input. Lake circulation and thermal structure are calculated using a three-dimensional hydrodynamic prediction model. Output from the model is used to provide information on the current state of the lake and to predict changes for the next two days. Currently, nowcast data is being produced for Lake Erie and being made available to CoastWatch data users. Figure 5, an example output from the Great Lakes Forecasting System, illustrates temperature profiles.

SST ALGORITHMS/VERIFICATION

Since 1990, three computer procedures have been used by NESDIS to create and map Great Lakes surface temperature images: SSTMAP, IMGMAP, and OCNMAP. These algorithms have employed both linear and non-linear, split and triple window equations, and different coefficients to account for changing atmospheric parameters and are described by Leshkevich et al. (1993). In this section, the OCNMAP algorithms and coefficients used since September 14, 1993 are described.

SST ALGORITHMS

The OCNMAP procedure (operational since 1992) uses two sets of equations for Great Lakes temperature imagery: a linear, split window MCSST equation for the daytime pass and a non-linear, split window NLSST equation for the nighttime pass. The equations and coefficients used for NOAA-11 since September 14, 1993 are:

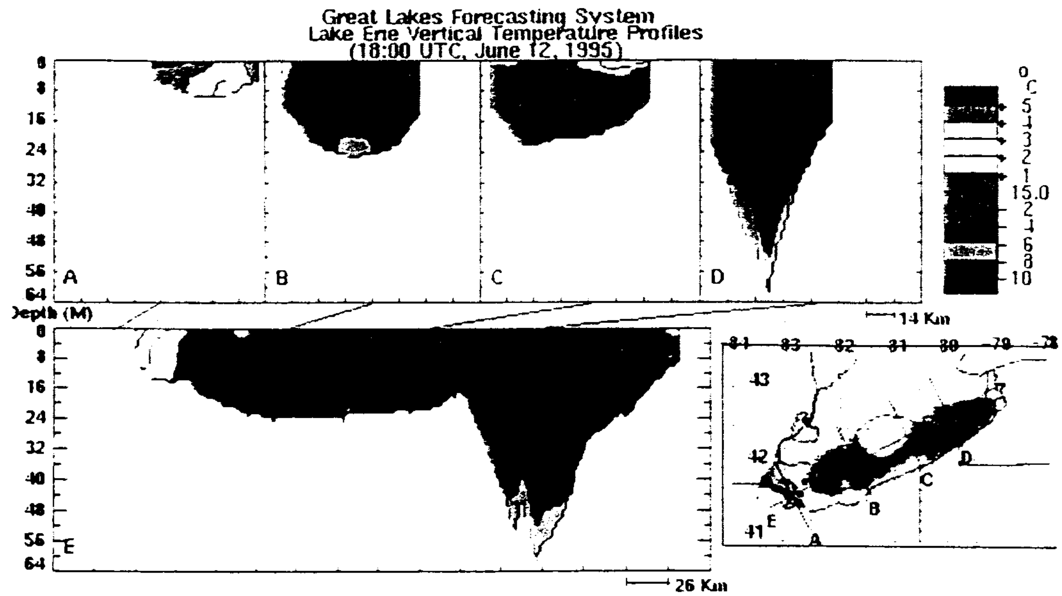
Daytime split-window:

$$MCSST = 0.979224\,(T4) + 2.361743\,(T4-T5) + 0.33084\,(T4-T5)\,(\sec\theta - 1) - 267.029 \quad (1)$$

Nighttime split-window:

$$NLSST = 0.899907\,(T4) + 0.091549\,(T4-T5)\,(MCSST) + 0.647912\,(T4-T5)\,(\sec\theta - 1) - 243.821 \quad (2)$$

Figure 5. Lake Erie vertical temperature profiles, derived from the Great Lakes Forecasting System. (Courtesy of Keith Bedford, Dept. of Civil and Environmental Engineering and Geodetic Science, The Ohio State University, Columbus, Ohio).



where MCSST is the nighttime linear split-window SST equation:

$$\begin{aligned} MCSST = {} & 0.978971\ (T4) \\ & + 2.593454\ (T4\text{-}T5) \\ & + 0.623203\ (T4\text{-}T5)\ (\sec\theta - 1) \\ & - 267.542 \end{aligned} \tag{3}$$

where SST is in °C, T4 and T5 are channel 4 and channel 5 brightness temperatures in °K, and secθ is secant of the satellite zenith angle.

The equations and coefficients used for NOAA-12 since March 14, 1994 are:

Daytime split-window:

$$\begin{aligned} MCSST = {} & 0.963563\ (T4) \\ & + 2.579211\ (T4\text{-}T5) \\ & + 0.242598\ (T4\text{-}T5)\ (\sec\theta - 1) \\ & - 263.006 \end{aligned} \tag{4}$$

Nighttime split-window:

$$\begin{aligned} NLSST = {} & 0.888706\ (T4) \\ & + 0.081646\ (T4\text{-}T5)\ (MCSST) \\ & + 0.576136\ (T4\text{-}T5)\ (\sec\theta - 1) \\ & - 240.229 \end{aligned} \tag{5}$$

where MCSST is the nighttime linear split-window SST equation:

$$\begin{aligned} MCSST = {} & 0.967077\ (T4) \\ & + 2.384376\ (T4\text{-}T5) \\ & + 0.480788\ (T4\text{-}T5)\ (\sec\theta - 1) \\ & - 263.94 \end{aligned} \tag{6}$$

where SST is in °C, T4 and T5 are channel 4 and channel 5 brightness temperatures in °K, and secθ is secant of the satellite zenith angle.

The equations and coefficients used for NOAA-14 since March 22, 1995 are:

Daytime split-window:

$$\begin{aligned} MCSST = {} & 1.017342\ (T4) \\ & + 2.139588\ (T4\text{-}T5) \\ & + 0.779706\ (T4\text{-}T5)\ (\sec\theta - 1) \\ & - 278.43 \end{aligned} \tag{7}$$

Nighttime split-window:

$$\begin{aligned} NLSST = {} & 0.933109\ (T4) \\ & + 0.078095\ (T4\text{-}T5)\ (MCSST) \\ & + 0.738128\ (T4\text{-}T5)\ (\sec\theta - 1) \\ & - 253.428 \end{aligned} \tag{8}$$

where MCSST is the nighttime linear split-window SST equation:

$$\begin{aligned} MCSST = {} & 1.029088\ (T4) \\ & + 2.275385\ (T4\text{-}T5) \\ & + 0.752567\ (T4\text{-}T5)\ (\sec\theta - 1) \\ & - 282.24 \end{aligned} \tag{9}$$

where SST is in °C, T4 and T5 are channel 4 and channel 5 brightness temperatures in °K, and secθ is secant of the satellite zenith angle.

VERIFICATION

Initial verification of Great Lakes CoastWatch surface temperature data for two periods (May 1990 through May 1991 (SSTMAP) and June 1991 through February 1992 (IMGMAP)) and for initial OCNMAP data was conducted at GLERL by comparing the satellite-derived surface temperatures with water temperature data recorded by

NOAA Data Buoy Center (NDBC) weather buoys. Results are described by Leshkevich et al. (1993). Currently, validation of the accuracy of CoastWatch products is being conducted by NESDIS for all CoastWatch regional sites. The validation procedure and results from the validation of NOAA-12 and NOAA-14 are described by Pichel et al. (1995).

COASTWATCH SYSTEM COMPONENTS

A number of CoastWatch system components and services are shared among the eight CoastWatch Regional Sites (See Figure 1). At GLERL, as at other east coast and Gulf nodes, image files centrally processed on the Central Environmental Satellite Computer System (CEMSCS) at NESDIS using AVHRR HRPT data received by the Command and Data Acquision (CDA) Station at Wallops Station, Virginia, are downloaded daily via Internet, stored on a computer, and made available to local CoastWatch users over Internet or over dial-in telephone lines. Satellite image data are normally available at GLERL within about five hours of when it was acquired by the satellite sensor. At 9600 baud, a 300 Kbyte image file takes approximately five to ten minutes to download. Over INTERNET (at 56 K baud), the same file takes about one to two minutes to download. Image files for the previous two months are kept online and are available to local CoastWatch participants. After that period, image files are available from an archive at the NOAA Ocean Data Center (NODC). The NOAA CoastWatch Active Access System (NCAAS) has been developed specifically for the CoastWatch program and serves as the data archive for all Regional Sites.

CoastWatch image files can be displayed and analyzed on computer hardware and software systems of varying capabilities. The minimum system requirements are a 286 or 386 personal computer (PC) with a VGA monitor. In addition to commercially available image processing systems, a number of public domain and shareware software packages are available, including two developed by NESDIS specifically for CoastWatch image data. The VGA Image Desktop Analysis System (VIDAS) requires a minimum configuration of a desktop PC with a VGA monitor (Urbanski and Dennis, 1992). Another system, the Interactive Digital Image Display and Analysis System (IDIDAS) requires a proprietary graphics card and a 512 × 512 color monitor in addition to a PC with VGA monitor. This system has display, shift image (geocorrection), analysis, annotation, and print capabilities and is described by Celone and Tseng (1991). Developed in cooperation with NASA, CCOAST is another PC-based image display and analysis package distributed to CoastWatch data users (Miller and DeCampo, 1994). Software to uncompress, display, and analyze CoastWatch imagery is also available for Unix-based workstations, but often requires proprietary software.

SUMMARY

CoastWatch, a NOAA-wide program, is designed to provide near real-time access to satellite imagery, image products, and *in situ* environmental data for U.S. coastal regions to support federal and state decision makers and researchers who are responsible for managing the Nation's living marine resources and ecosystems. In 1990, the Great Lakes region became part of the CoastWatch program. The initial CoastWatch product for the Great Lakes was digital imagery of lake surface temperature derived from NOAA AVHRR satellite data and mapped into four 512 × 512 pixel "scenes" covering the lakes at 1.3 and 2.6 km resolution. During the period April 1990 to May 1995, over 32,000 images (from SSTMAP, IMGMAP, and OCNMAP procedures) for these four scene areas were processed and received electronically. The current Great Lakes CoastWatch product suite of images, continually being verified for accuracy, along with marine observation data, water level gauge data, and Great Lakes Forecasting System output, will be enhanced in the future with products, such as ocean color and ice analysis and mapping, based on new satellite sensors such as SeaWiFS, ADEOS/OCTS, and Synthetic Aperature Radar (Leshkevich et al., 1994, Leshkevich et al., in press). PC-based software is available to read, display, and help analyze CoastWatch image data.

ACKNOWLEDGMENT

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